

## Searches for phenomena beyond the Standard Model at the LHC with the ATLAS and CMS detectors

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**Abstract.** The LHC has delivered several  $\text{fb}^{-1}$  of data in spring and summer 2011, opening new windows of opportunity for discovering phenomena beyond the Standard Model. A summary of the searches conducted by the ATLAS and CMS experiments based on about  $1 \text{ fb}^{-1}$  of data is presented.

**Keywords.** LHC, ATLAS, CMS, BSM, Supersymmetry, Exotic

### 1. Introduction

The Standard Model (SM) has proven to be an incredibly successful theory over the past decades. However successful, it is an effective theory that must break down above a certain energy scale, and there are strong theoretical arguments to believe that it breaks down at the electroweak scale. For a theoretical review of this subject, see [1] and the contribution in this conference from the same author. In 2011, operating at a center-of-mass energy of 7 TeV in  $pp$  collisions, the LHC has been able to deliver several  $\text{fb}^{-1}$  of data to both ATLAS [2] and CMS [3] detectors within a few months, allowing to extend the reach of searches for phenomena beyond the Standard Model well beyond the ones carried by the TeVatron.

This article presents some of the searches carried by ATLAS and CMS using up to  $1.6 \text{ fb}^{-1}$  of data on supersymmetry and exotic signatures. I will start with a summary of the searches for supersymmetry, followed by an overview of some exotic searches, divided somewhat arbitrarily in three sections: search for heavy resonances, search for strong gravity at the TeV-scale, and search for long-lived particles. Unfortunately no deviation from the SM expectation is observed, but limits on many theories beyond the SM are improved significantly.

Searches related to Higgs boson, top-antitop resonance and fourth generation quarks are described in other contributions of this conference [4–6]. Only a selection of results is shown here; all results can be found on the ATLAS [7] and CMS [8] web pages.

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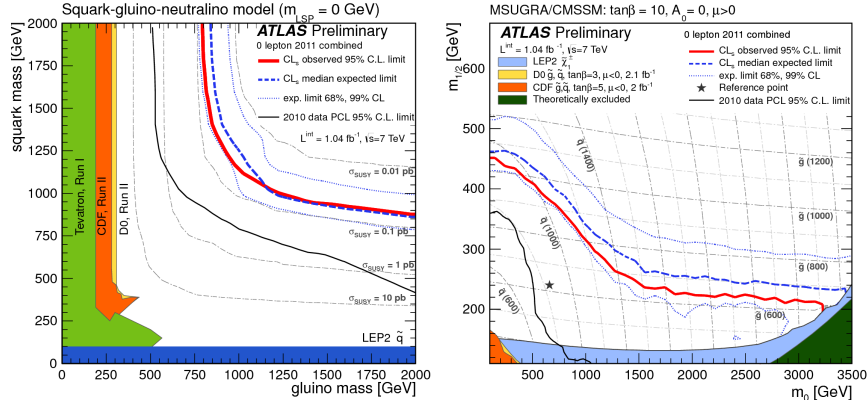
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## 2. Supersymmetry

During the past decades, supersymmetry [9, 10] has been considered the most promising extension of the SM. The phenomenology of supersymmetry is very diverse, which requires a search strategy following several classes of models and covering many signatures.

In its most hoped for incarnation, supersymmetry is expected to be discovered at the LHC through pair production of supersymmetric particles decaying in a cascade of supersymmetric and SM particles. If R-parity is conserved, the lightest supersymmetric particle (LSP) is stable and neutral, and the cascade ends with the production of LSP's, which escape the detector, producing missing transverse momentum.

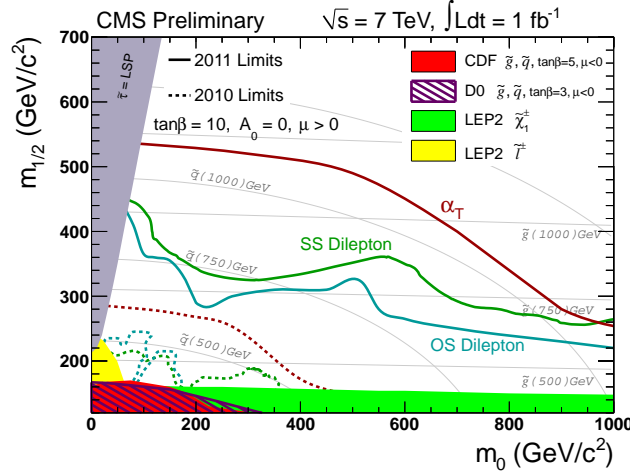
In  $pp$  collisions, strongly coupled particles are much more likely to be produced, thus the production of squarks and gluinos is expected to dominate, leading predominantly to a final state with jets and missing transverse momentum. The “workhorse” of supersymmetry searches at the LHC is thus the channel with large missing transverse momentum and jets of high transverse momentum. No excess above the expected SM background is observed and limits are set on supersymmetric models. Figures 1 and 2 show the limits from ATLAS [11] and CMS [12]. In addition to setting limits on the CMSSM/MSUGRA model, ATLAS also presents a limit for a simplified model assuming only squark and gluino production, and a cascade involving only quarks and gluons, and the LSP. For equal masses of squarks and gluinos, a limit of about 1 TeV is set at 95% CL.



**Figure 1.** Limits on supersymmetric models from the 0-lepton channel at ATLAS [11]. Left: simplified model assuming only squark and gluino production, and a light LSP. Right: CMSSM/MSUGRA model.

The cascade can also produce leptons through the decay of sleptons, charginos, or W/Z bosons. Due to the smaller branching ratio, channels containing one [13, 14] or more electron or muon are less sensitive to squark and gluino strong production, but are complementary to the fully hadronic channel, as shown in Figure 2 for the CMS results. In the di-lepton channel, several strategies are employed: opposite-sign [15] or same-sign [16], flavor subtraction [17] to remove the flavor-correlated background, or explicit reconstruction of a Z produced in the cascade and decaying to a pair of muons or electrons [18].

Of particular interest are scenarios in which the third generation of supersymmetric particles is much lighter than the others. The current luminosity allows to test such sce-



**Figure 2.** Summary of the searches for supersymmetry at CMS on CMSSM/MSUGRA in the 0-lepton, 1-lepton, and 2-lepton channel.

narios only through production of gluinos decaying to stop or sbottom, leading to a final state of top and/or bottom quarks. Assuming that the stop is the only light squark, gluino pair production leads to a complex final state containing top and bottom quarks. Figure 3 (top) shows that this scenario is excluded for gluino masses up to 500 GeV in the channel with one lepton and at least four jets, one of which identified as a b-jet [19]. Alternatively, if the only light squark is a sbottom, gluino pair production leads to a final state with four b-jets and two LPS's; in this case, in the channel with at least 3 jets, at least two of which identified as b-jets, gluino masses are excluded up to 700 GeV, as shown on Figure 3 (bottom) [20]. Additional luminosity will allow to search for direct production of third generation quarks and gauginos.

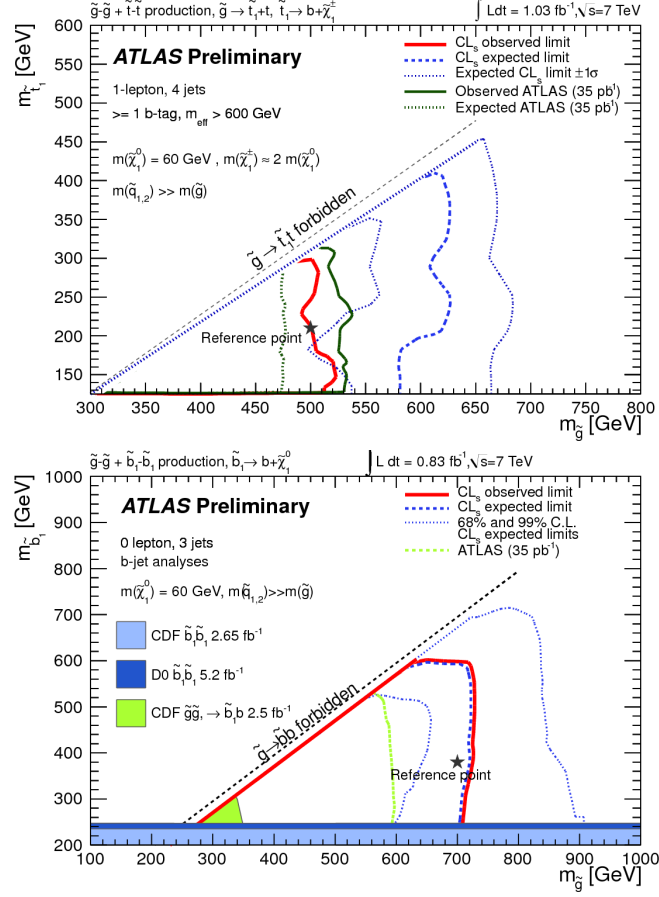
In gauge-mediated supersymmetry breaking (GMSB) models [21], the LSP is the gravitino and the next lightest supersymmetric particle (NLSP) is a neutralino or a chargino. This leads to a cascade ending with photons and missing transverse momentum in the final state. CMS has looked for both single-photon and di-photon final states [22]. Results are shown in Figure 4. In the di-photon channel, the result is also interpreted for the scenario of wino-like NLSP (neutralino and chargino nearly degenerate in mass). Universal Extra-Dimensions (UED) models [23] predict cascades that are very similar to supersymmetry, which allows to interpret the same analysis in both models [24].

Supersymmetric signatures involving long-lived particles are discussed in the last section.

### 3. Heavy resonances

Heavy resonances are predicted by many extensions of the SM. Some Grand Unified Theories [25] predict the existence of additional gauge bosons while Randall-Sundrum models with warped extra-dimensions [26, 27] predict Kaluza-Klein excitations of the graviton. Both lead to a narrow resonance decaying to a pair of fermions or bosons with branching ratios varying widely depending on the model considered.

In the di-lepton channel (di-electron or di-muon) [28, 29], a neutral gauge boson with

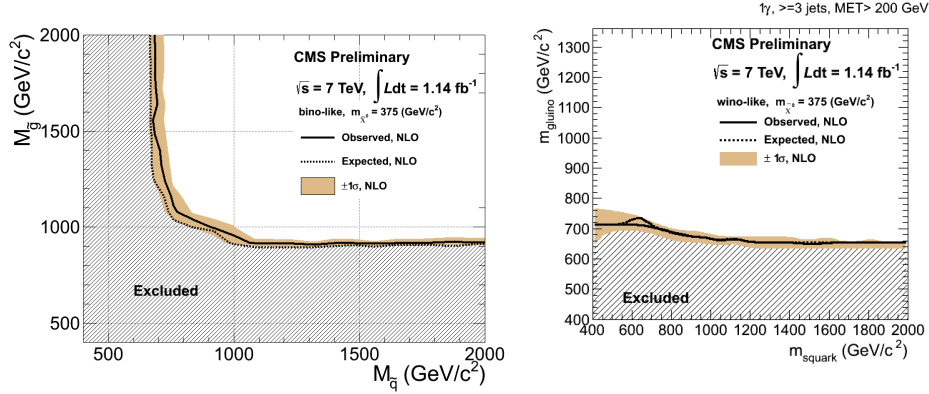


**Figure 3.** Search for light third generation supersymmetric models. Top: 1-lepton with at least one b-jet [19]. Bottom: 0-lepton with b-jets [20].

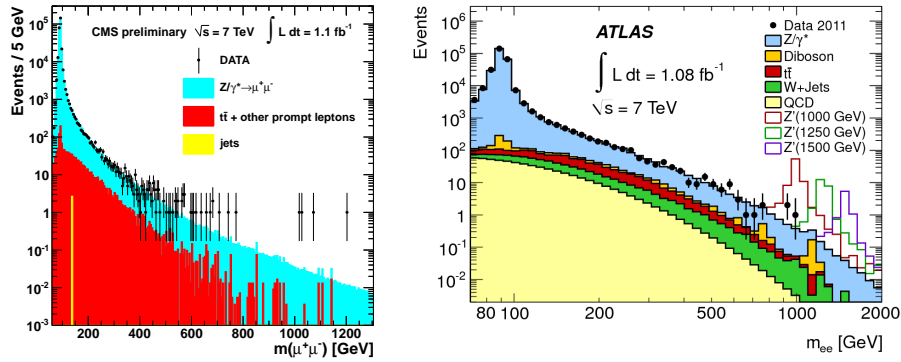
the same couplings as the SM  $Z^0$  (Sequential Standard Model  $Z'$  [30]) is excluded up to a mass of 1.9 TeV at 95% CL. A Randall-Sundrum Kaluza-Klein graviton with a coupling of  $k/M_{Pl} = 0.1$  is excluded up to 1.8 TeV at 95% CL combining the di-electron and the di-muon channel, and up to 1.7 TeV in the diphoton channel alone [31]. Figure 5 and figure 6 (left) show the di-leptons and the di-photon mass spectra, respectively.

A charged gauge boson ( $W'$ ) is searched for in the  $e\nu$  and  $\mu\nu$  channels by reconstructing the transverse mass of the lepton transverse momentum and the event missing transverse momentum. Figure 6 (right) shows the ATLAS transverse mass in  $\mu\nu$  events. A  $W'$  with the same couplings as the SM  $W$  (Sequential Standard Model  $W'$ ) is excluded up to a mass of 2.3 TeV at 95% CL when combining  $e\nu$  and  $\mu\nu$  channels [32, 33]. A  $W'$  is also expected to decay to  $WZ$ , which is also a channel of interest for Technicolor [34] searches; CMS has looked for a narrow resonance in the final state  $WZ \rightarrow l\nu ll$  and excludes an SSM  $W'$  up to a mass of 784 GeV and a techni-rho up to a mass of 436 GeV in the parameter space  $m_{\rho_{TC}} < m_{\pi_{TC}} + m_W$  [35].

A narrow resonance decaying to a pair of jets is also predicted by numerous models. Considering the excited quark model ( $q^*$ ) [36] as a benchmark, no narrow resonance



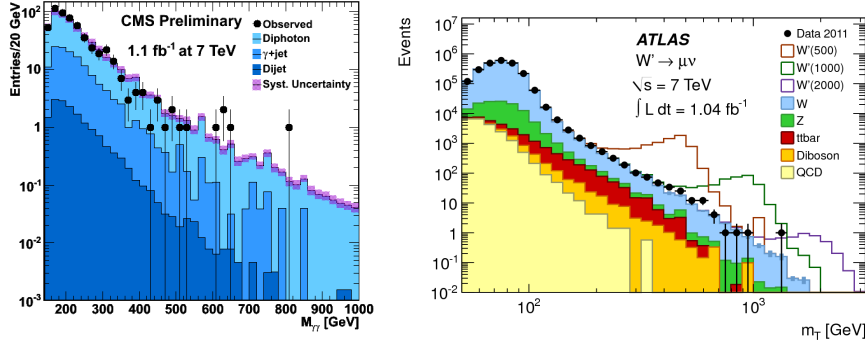
**Figure 4.** Search for GMSB in the single-photon plus missing transverse momentum and diphoton plus missing transverse momentum final states [22]. Left: di-photon, bino-like interpretation. Right: single photon, wino-like interpretation.



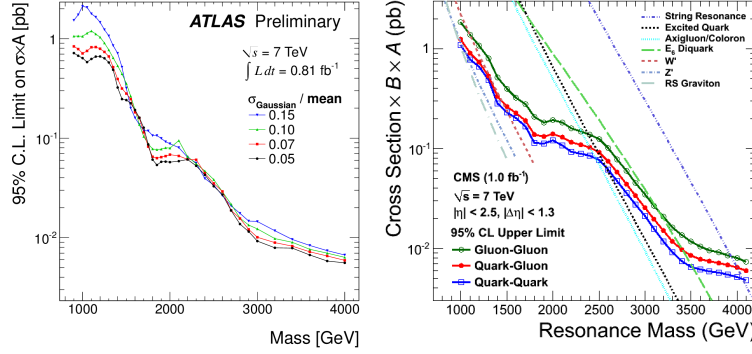
**Figure 5.** Search for heavy resonances in the di-lepton channel. Left: reconstructed di-muon mass spectrum (CMS) [29]. Right: reconstructed di-electron mass spectrum (ATLAS) [28].

in the di-jet system is observed up to 2.9 TeV at 95% CL [37, 38]. Figure 7 shows the ATLAS model-independent limit on the cross-section for several hypotheses of the resonance width, and the CMS limits on several models depending on the nature of the jet (quark jet or gluon jet).

A heavy particle decaying to a pair of charged leptons of same-sign, such as a doubly-charged Higgs, would be a striking signature of physics beyond the SM. More generally, final states including a pair of charged leptons of same-sign are predicted by many BSM models (including supersymmetry, same-sign top production, fourth generation  $b'$ , heavy Majorana neutrino, etc...) and enjoy a very small SM background. Thus an inclusive search for same-sign di-lepton pair is very sensitive to a wide range of models, and thanks to the small background is almost as sensitive as a search optimized for a particular model. With  $1.6 \text{ fb}^{-1}$  of integrated luminosity, ATLAS sets a model-independent limit on the fiducial cross-section of isolated pairs of same-sign muons as a function of the di-lepton pair mass [39] as shown on Figure 8. The same mass spectrum is used to search for



**Figure 6.** Left: Di-photon reconstructed mass spectrum (CMS) [31]. Right: reconstructed transverse mass in events with one muon and missing transverse momentum (ATLAS) [32].



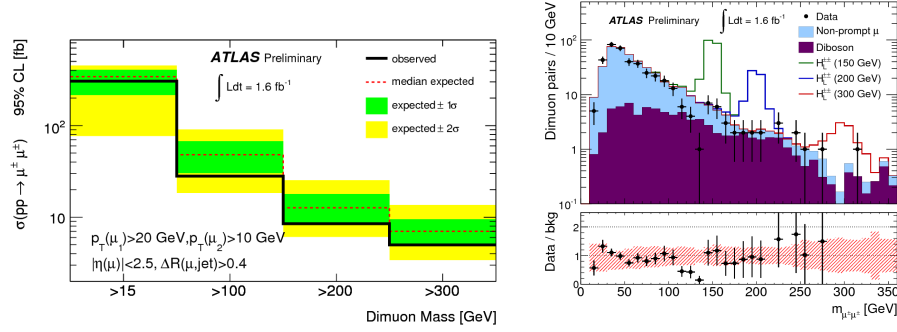
**Figure 7.** 95% CL upper limits on the production cross-section times acceptance of resonances decaying to a pair of jets. Left: the limit is presented in a model-independent way as a function of the full width (both physical and experimental) of the resonance (ATLAS) [37]. Right: limits on narrow resonances of type gluon-gluon, gluon-quark, and quark-quark are compared to various theoretical predictions (CMS) [38].

a narrow resonance, allowing to exclude doubly-charged Higgs pair production up to a mass of 375 GeV in the left-handed coupling triplet model [40].

#### 4. Strong gravity

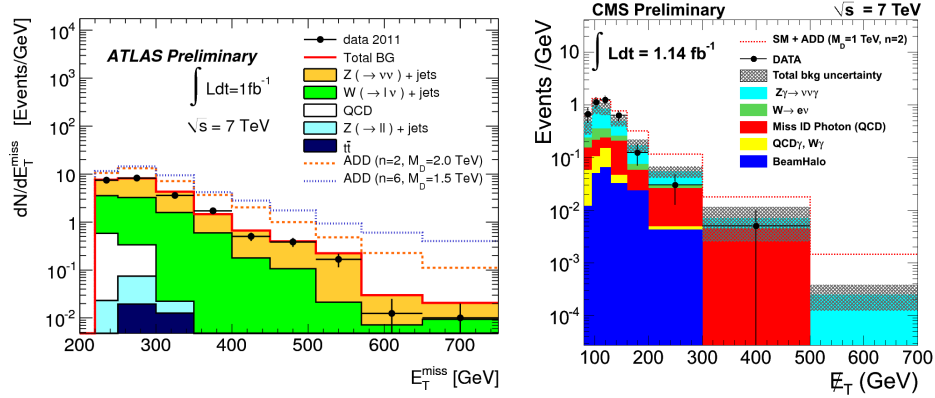
Theories of extra-dimension are a possible answer to the hierarchy problem. In the large extra-dimension ADD model [41], gravity is allowed to propagate into extra-dimensions, thus appearing weak at (spatial) scales much larger than the scale of the extra-dimensions, but possibly becoming strong at a scale of  $1/\text{TeV}$ . The fundamental mass scale  $M_D$  at which gravity becomes strong is related to the Planck scale via  $m_{Pl}^2 = m_D^{2+n} R^n$  where  $n$  is the number of extra-dimensions, and  $R$  is the size of the extra-dimension, and can indeed be close to the TeV scale for well-chosen values of  $n$  and  $R$ .

A promising signature at colliders is the production of a single graviton escaping the detector and recoiling against a jet or a photon, leading to mono-jet [42, 43] or mono-



**Figure 8.** Left: model-independent fiducial cross section limit on the production of same-sign di-muon pairs [39]. Right: reconstructed mass of same-sign muon pairs in ATLAS and expected doubly-charged Higgs signal of various masses [40].

photon [44] final states with large missing transverse momentum. Figure 9 shows the missing transverse momentum spectrum in the ATLAS mono-jet (left) and CMS mono-photon (right) analyses. Thanks to a larger cross-section the mono-jet channel gives the most stringent limits, excluding  $M_D$  up to 3.7 TeV for  $n = 2$  and 2.3 TeV  $n = 6$  (conservatively assuming LO cross-sections).

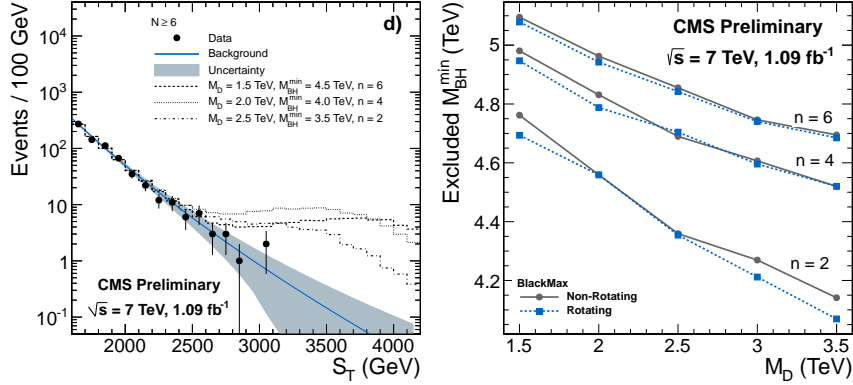


**Figure 9.** Missing transverse momentum in ATLAS mono-jet (left) and CMS mono-photon (right) analyses [42, 43].

Another signature of ADD extra-dimensions is a non-resonant enhancement of expected di-lepton and di-photon events at high invariant mass through virtual graviton exchange. CMS has searched for deviations in the di-muon [45] and di-photon [46] spectra, with a sensitivity similar to the monojet channel.

Finally, if gravity becomes strong at the TeV scale, microscopic black-holes may be produced at the LHC. Due to our lack of understanding of quantum gravity, it is impossible to make precise predictions of such phenomena. However one can expect such objects to decay democratically and isotropically, leading to a final state with a large multiplicity of high-momentum particles, and a high content of leptons. Several channels have been considered: multi-jet [47], same-sign di-muon with a high track multiplicity [48], and

multi-object [49] (where an object refers to an electron, a muon, a photon, or a jet, and a large number of objects is required in the event). In the latter case, CMS sets limits on black-hole masses up to 4-5 TeV for some classes of models. Figure 10 shows the  $S_T$  variable, defined as the scalar sum of the transverse momentum of all objects in the event, for events with at least six objects (left), and the limits achieved on the black-hole mass (right).



**Figure 10.** Multi-object search for microscopic black-holes at CMS [49]. Left: Scalar sum of all objects transverse momentum in events with at least six objects. Right: Limit on black-hole mass as a function of  $M_D$ , number of extra-dimensions, for two black-hole models.

## 5. Long-lived particles

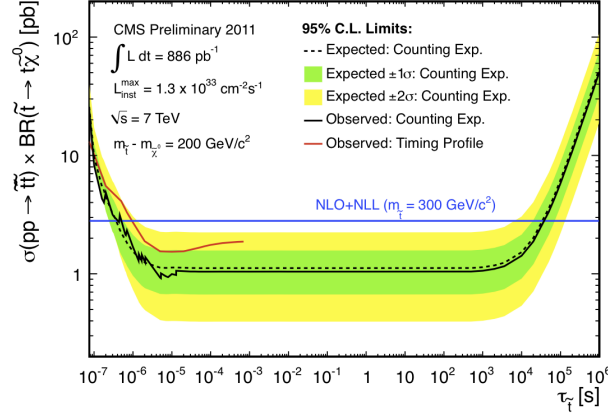
Several extensions of the SM, including Hidden Valley models [50], and supersymmetry in some scenarios [51], predict the existence of long-lived heavy particles. In the case of supersymmetry, a long-lived gluino or squark hadronizes into hadronic states called R-hadrons. The experimental signature depends strongly on the property of the particle, and in particular its life-time. If the life-time is short (between 1 ps and several ns) the particle decays within the detector in time with the collision that produced it; in this case it is possible to identify the decay thanks to dedicated vertexing [52].

If the particle life-time is much longer than 1 ns there is no hope to see it decay in the detector. If the particle is charged, it is possible to take advantage of the properties of a slow heavy particle and identify it thanks to high energy loss in the tracking detectors and long time-of-flight [53]. Alternatively, for a life-time up to about 1 month, if the particle is stopped within the detector, it is possible to observe its decay long after the collision that produced it occurred [54]. Figure 11 shows the limit on the production of long-lived scalar top stopping in the detector and decaying out-of-time; the analysis is sensitive over 13 orders of magnitudes, from 100 ns to 1 month.

## 6. Conclusion

The LHC has performed exceptionally well and has provided ATLAS and CMS with more luminosity than expected. Many searches for physics beyond the SM have been conducted with up to  $1.6 \text{ fb}^{-1}$ , covering a wide range of signatures. Unfortunately no





**Figure 11.** Search for out-of-time decay of heavy long-lived particles stopped in the detector: limit on the cross section times branching ratio as a function of the stop life-time [54].

deviation from the SM has been observed so far. Supersymmetry in its most hoped-for incarnation is starting to be pushed to the boarder of fine-tuning: in the framework of the CMSSM, supersymmetry is excluded up to a mass of 1 TeV in the (optimistic) scenario of equal squark-gluino mass. This opens the field to variations of supersymmetry that require more luminosity or new search strategies. Heavy gauge bosons are excluded up to masses of about 2 TeV, while quark compositeness is tested up to 3 TeV.

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## References

- [1] G. Bhattacharyya, arXiv:hep-ph/0910.5095, Rept.Prog.Phys.74:026201,2011
- [2] ATLAS Collaboration, JINST 3, S08003 (2008)
- [3] CMS Collaboration, JINST 3, S08004 (2008)
- [4] A. Nisati, in these proceedings
- [5] A. De Roeck, in these proceedings
- [6] J. Pilcher, in these proceedings
- [7] <https://twiki.cern.ch/twiki/bin/view/AtlasPublic>
- [8] <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults>
- [9] Y. Golfand and E. Likhtman, JETP Lett. 13 (1971) 323
- [10] J. Wess and B. Zumino, Nucl. Phys. B70 (1974) 39
- [11] ATLAS Collaboration, arXiv:hep-ex/1109.6572, submitted to PLB
- [12] CMS Collaboration, arXiv:hep-ex/1109.2352, Phys. Rev. Lett. 107 (2011) 221804
- [13] ATLAS Collaboration, arXiv:hep-ex/1109.6606, Phys. Rev. D 85 (2012) 012006
- [14] CMS Collaboration, CMS-PAS-SUS-11-015, <https://cdsweb.cern.ch/record/1380922>
- [15] CMS Collaboration, CMS-PAS-SUS-11-011, <https://cdsweb.cern.ch/record/1370065>
- [16] CMS Collaboration, CMS-PAS-SUS-11-010, <https://cdsweb.cern.ch/record/1370064>

- [17] ATLAS Collaboration, arXiv:hep-ex/1110.6189, accepted by PLB
- [18] CMS Collaboration, CMS-PAS-SUS-11-017, <https://cdsweb.cern.ch/record/1370066>
- [19] ATLAS Collaboration, ATLAS-CONF-2011-130, <https://cdsweb.cern.ch/record/1383833>
- [20] ATLAS Collaboration, ATLAS-CONF-2011-098, <https://cdsweb.cern.ch/record/1369212>
- [21] P. Meade, N. Seiberg, and D. Shih, Prog. Theor. Phys. Suppl. 177 (2009) 143
- [22] CMS Collaboration, CMS-PAS-SUS-11-009, <https://cdsweb.cern.ch/record/1377324>
- [23] T. Applequist, H.C. Cheng, and B.A. Dobrescu, Phys. Rev. D64 (2001) 035002
- [24] ATLAS Collaboration, arXiv:hep-ex/1107.0561, EPJC 71 (2011) 1744
- [25] D. London and J. L. Rosner, Phys. Rev. D34 (1986) 1530
- [26] L. Randall and R. Sundrum, arXiv:hep-th/9906064, Phys. Rev. Lett. 83 (1999) 4690
- [27] L. Randall and R. Sundrum, arXiv:hep-ph/9905221, Phys. Rev. Lett. 83 (1999) 3370
- [28] ATLAS Collaboration, arXiv:hep-ex/1108.1582, Phys.Rev.Lett. 107 (2011) 272002
- [29] CMS Collaboration, CMS-PAS-EXO-11-019, <https://cdsweb.cern.ch/record/1369192>
- [30] G. Altarelli, B. Mele, M. Ruiz-Altaba, Z. Phys. C 45 (1989) 109
- [31] CMS Collaboration, CMS-PAS-EXO-11-038, <https://cdsweb.cern.ch/record/1376706>
- [32] ATLAS Collaboration, arXiv:hep-ex/1108.1316, Phys.Lett.B 705 (2011) 28-46
- [33] CMS Collaboration, CMS-PAS-EXO-11-024, <https://cdsweb.cern.ch/record/1369201>
- [34] K. D. Lane and E. Eichten, Phys. Lett. B 222 (1989) 274
- [35] CMS Collaboration, CMS-PAS-EXO-11-041, <https://cdsweb.cern.ch/record/1377329>
- [36] U. Baur, I. Hinchliffe, and D. Zeppenfeld, Int. J. Mod. Phys. A 2 (1987) 1285
- [37] ATLAS Collaboration, ATLAS-CONF-2011-095, <https://cdsweb.cern.ch/record/1369186>
- [38] CMS Collaboration, arXiv:hep-ex/1107.4771, Phys. Lett. B 704 (2011) 123
- [39] ATLAS Collaboration, ATLAS-CONF-2011-126, <https://cdsweb.cern.ch/record/1383790>
- [40] ATLAS Collaboration, ATLAS-CONF-2011-127, <https://cdsweb.cern.ch/record/1383792>
- [41] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, Phys. Lett. B 429 (1998) 263
- [42] ATLAS Collaboration, ATLAS-CONF-2011-096, <https://cdsweb.cern.ch/record/1369187>
- [43] CMS Collaboration, CMS-PAS-EXO-11-059, <http://cdsweb.cern.ch/record/1376675>
- [44] CMS Collaboration, CMS-PAS-EXO-11-058, <http://cdsweb.cern.ch/record/1377334>
- [45] CMS Collaboration, CMS-PAS-EXO-11-039, <http://cdsweb.cern.ch/record/1376670>
- [46] CMS Collaboration, CMS-PAS-EXO-11-038, <http://cdsweb.cern.ch/record/1376706>
- [47] ATLAS Collaboration, ATLAS-CONF-2011-068, <https://cdsweb.cern.ch/record/1349309>
- [48] ATLAS Collaboration, ATLAS-CONF-2011-065, <https://cdsweb.cern.ch/record/1346080>
- [49] CMS Collaboration, CMS-PAS-EXO-11-071, <https://cdsweb.cern.ch/record/1369209>
- [50] M. J. Strassler and K. M. Zurek, Phys. Lett. B 651 (2007) 374
- [51] N. Arkani-Hamed and S. Dimopoulos, arXiv:hep-th/0405159, JHEP 06 (2005) 073
- [52] ATLAS Collaboration, arXiv:hep-ex/1109.2242, PLB 707 (2012) 478
- [53] CMS Collaboration, CMS-PAS-EXO-11-022, <http://cdsweb.cern.ch/record/1370057>
- [54] CMS Collaboration, CMS-PAS-EXO-11-020, <http://cdsweb.cern.ch/record/1369210>